Which Parts of Protoplanetary Disks are Susceptible to the Magnetorotational Instability?

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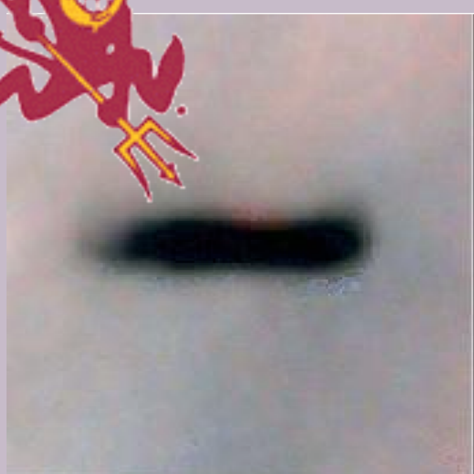


Outline

•Protoplanetary Disk Properties

•Magnetorotational Instability

•Limits on the Magnetorotational Instability

•The extent of the MRI in protoplanetary disks

Protoplanetary Disks

Masses / Surface Densities

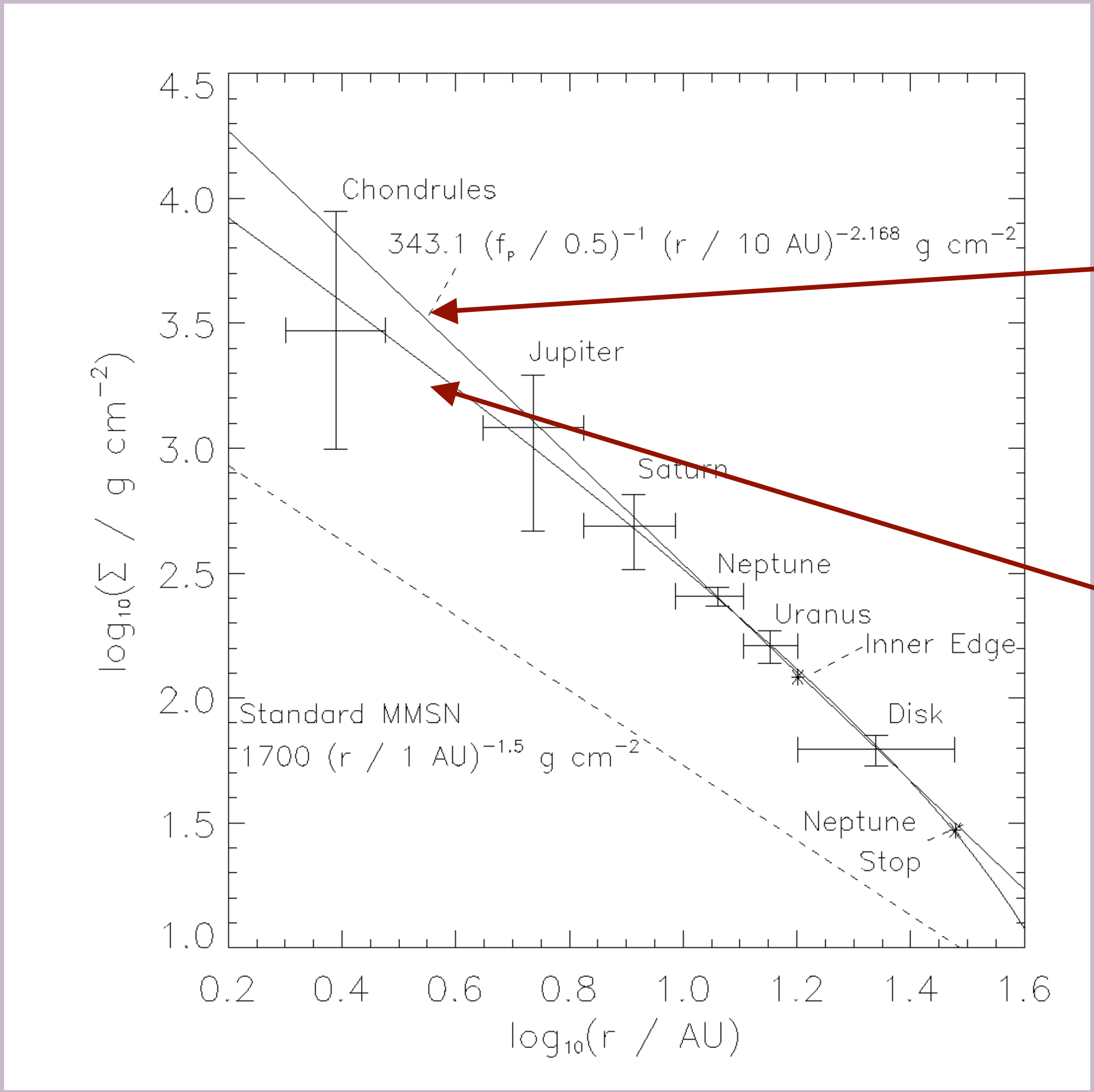
Millimeter fluxes yield median disk mass 0.005 $M_\odot$ in Taurus [Beckwith et al. 1990; Osterloh & Beckwith 1995; Andrews & Williams 2005] and Orion [Eisner & Carpenter 2006].

Caveats: these estimates assume **all** solids << 1 mm in size,and disks are optically thin. Disks are probably much more massive!

Minimum mass solar nebula [Weidenschilling 1977; Hayashi et al. 1985] requires at least 0.013 $M_\odot$ in disk to form planets.

Updated version [Desch 2007] accounting for planetary migration in 'Nice' model [Tsiganis et al. 2005; Gomes et al. 2005] shows solar nebula had to be even more massive, ~ 0.1 $M_\odot$

Protoplanetary Disks



Approximate solution:

$\Sigma(r) = 343\ (f_p/0.5)^{-1}$
$(r\ /\ 10\ \mathrm{AU})^{-2.17}\ \mathrm{g\ cm^{-2}}$

Consistent with steady state α decretion disk being photoevaporated at about 60 AU.

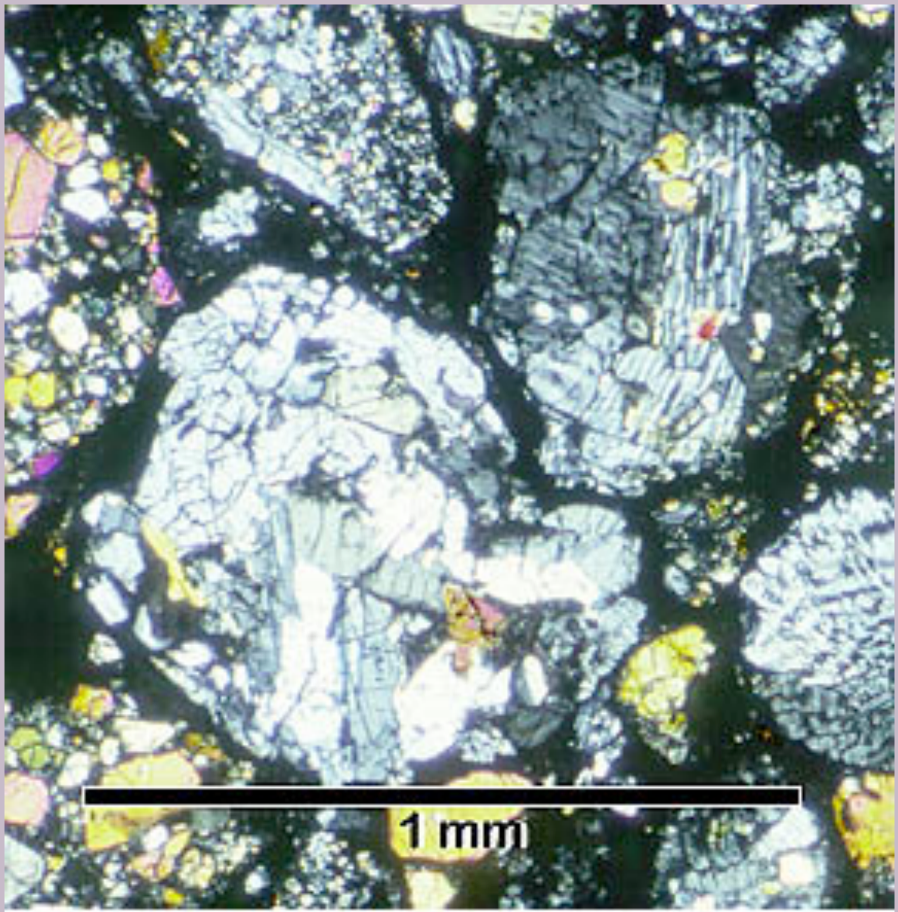
Total mass =
$0.1\ (f_p/0.5)^{-1}\ M_\odot$

Protoplanetary Disks

Size distribution of dust

Sub-micron dust commonly observed in T Tauri disks via 10 μm silicate emission features [e.g., Bouwman et al. 2008]

In chondrites, matrix grains ~ 0.1 - 1 μm in size, comprising half the mass of chondrites, co-genetic with chondrules forming > 2 Myr after solar system formation [e.g., Wood 1985; Wadhwa et al. 2007; MESS II]

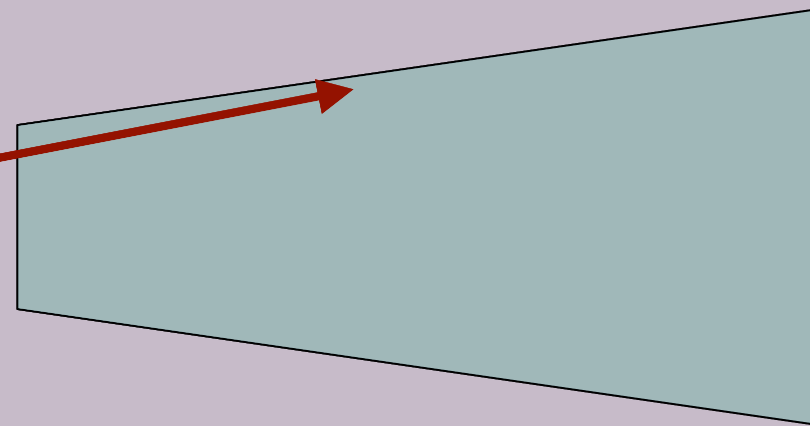


(photomicrograph by G. J. Taylor)

Protoplanetary Disks

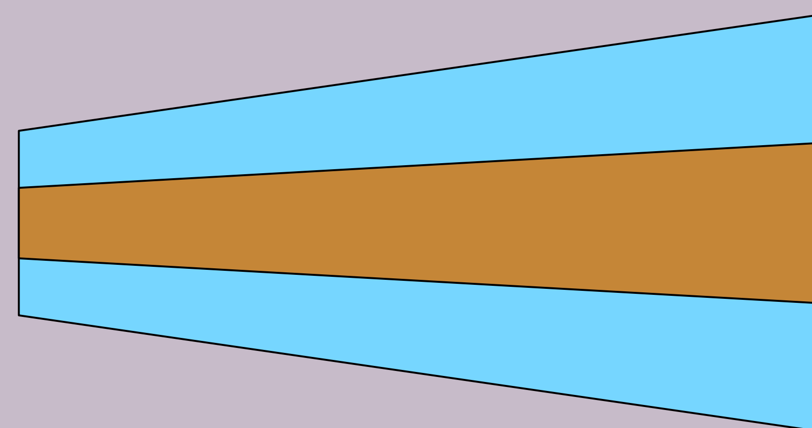
Spatial distribution of dust

Sub-micron dust observed via 10 μm silicate emission must be above most *dust*



But is it above the *gas*?!

More later.



Protoplanetary Disks

Magnetic Fields

Remanent magnetization of meteorites suggests B ~ 0.1 - 1 G in region where chondrites formed [Levy & Sonnett 1978]

Numerical simulations of molecular cloud core collapse suggest solar systems form with B ~ 0.1 G [Nakano & Umebayashi 1986a,b; Desch & Mouschovias 2001]

Wardle (2007) has shown that observed mass accretion rates of T Tauri disks demand B ~ 0.1 - 1 G

Orientation unknown, but presumed to start perpendicular to field, with net flux

Protoplanetary Disks

Turbulence

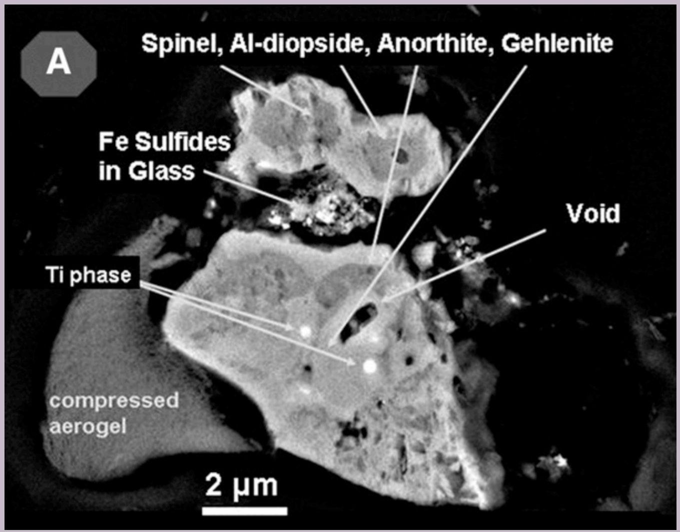
T Tauri disks in Taurus observed to viscously spread with $\alpha \sim 10^{-2}$ [Hartmann et al. 1998]

Chondrules within chondrites appear to be size-sorted by turbulence [Cuzzi et al. 2001]. Strength of turbulence consistent with $\alpha \sim 4 \times 10^{-4}$ [Desch 2007]

Radial mixing was widespread.

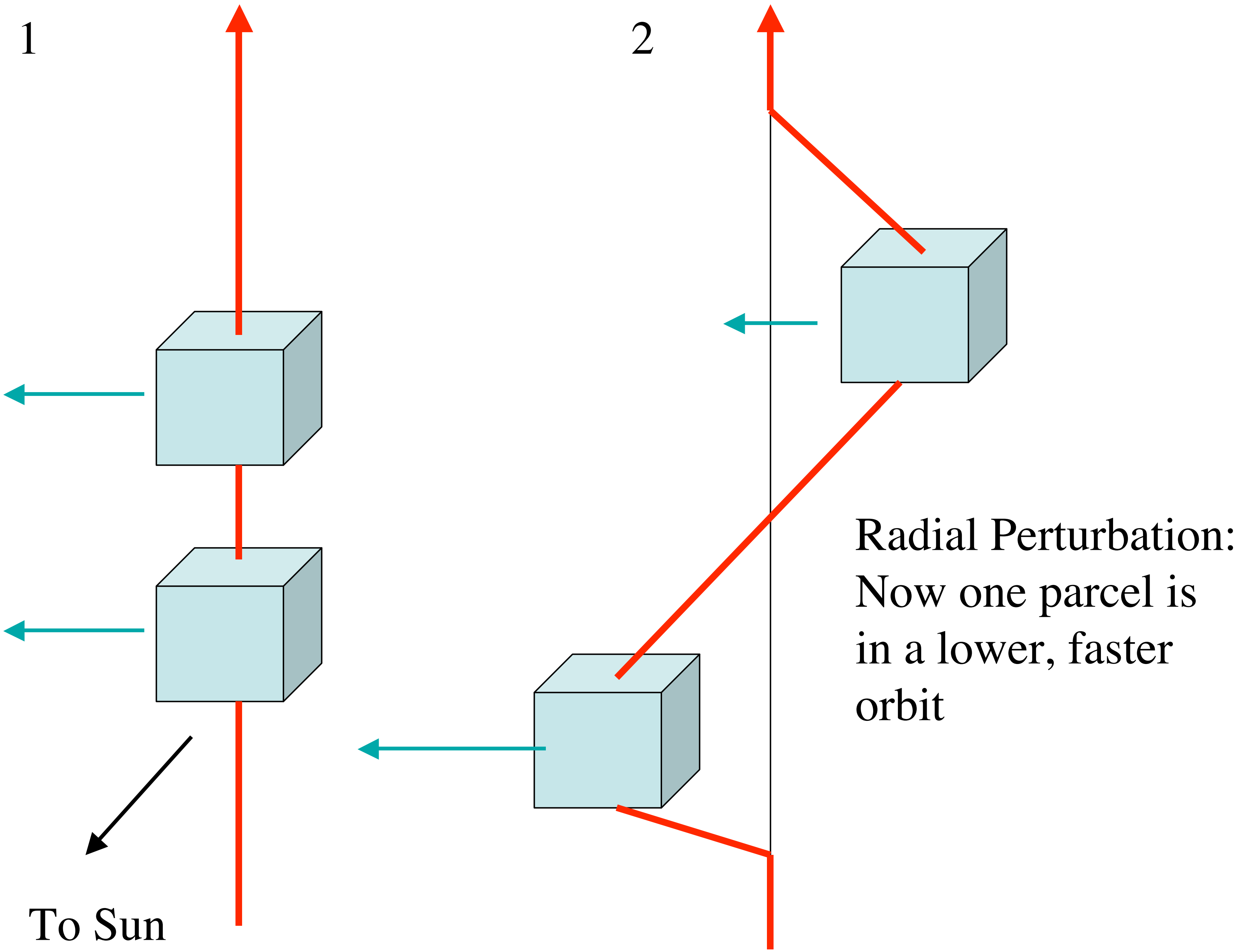
CAI-like grains formed in the inner solar nebula ended up in comets! [Zolensky et al. 2006]

If viscously mixed, $\alpha >\sim 10^{-3}$



Magnetorotational Instability

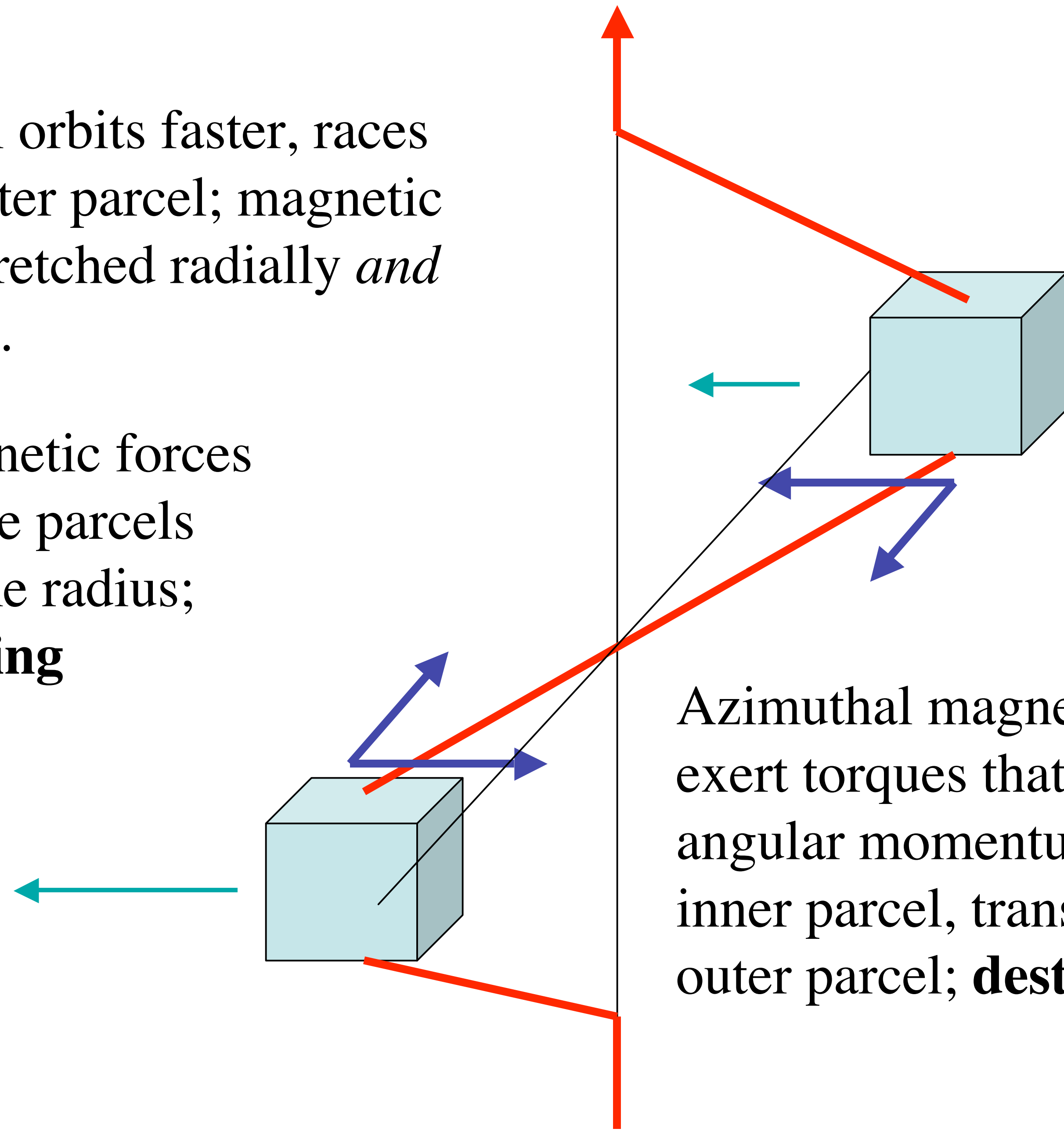
How it works


1
2
Radial Perturbation:
Now one parcel is
in a lower, faster
orbit
To Sun

3

Inner parcel orbits faster, races ahead of outer parcel; magnetic fields are stretched radially *and* azimuthally.

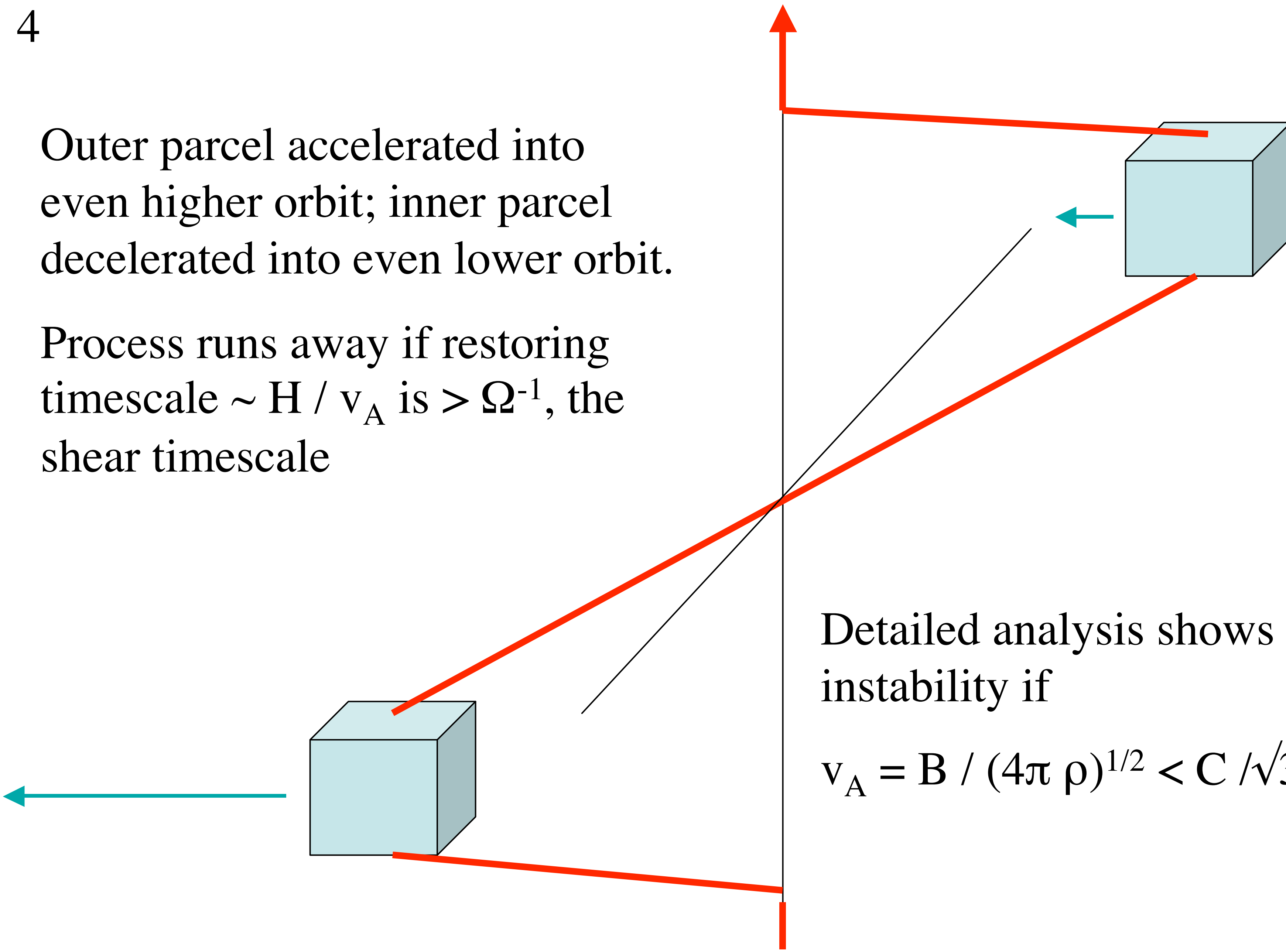
Radial magnetic forces try to restore parcels back to same radius; are **stabilizing**



Azimuthal magnetic forces exert torques that remove angular momentum from inner parcel, transfer it to outer parcel; **destabilizing**

Outer parcel accelerated into even higher orbit; inner parcel decelerated into even lower orbit.

Process runs away if restoring timescale ~ H / v_A is > Ω^{-1}, the shear timescale



Detailed analysis shows instability if

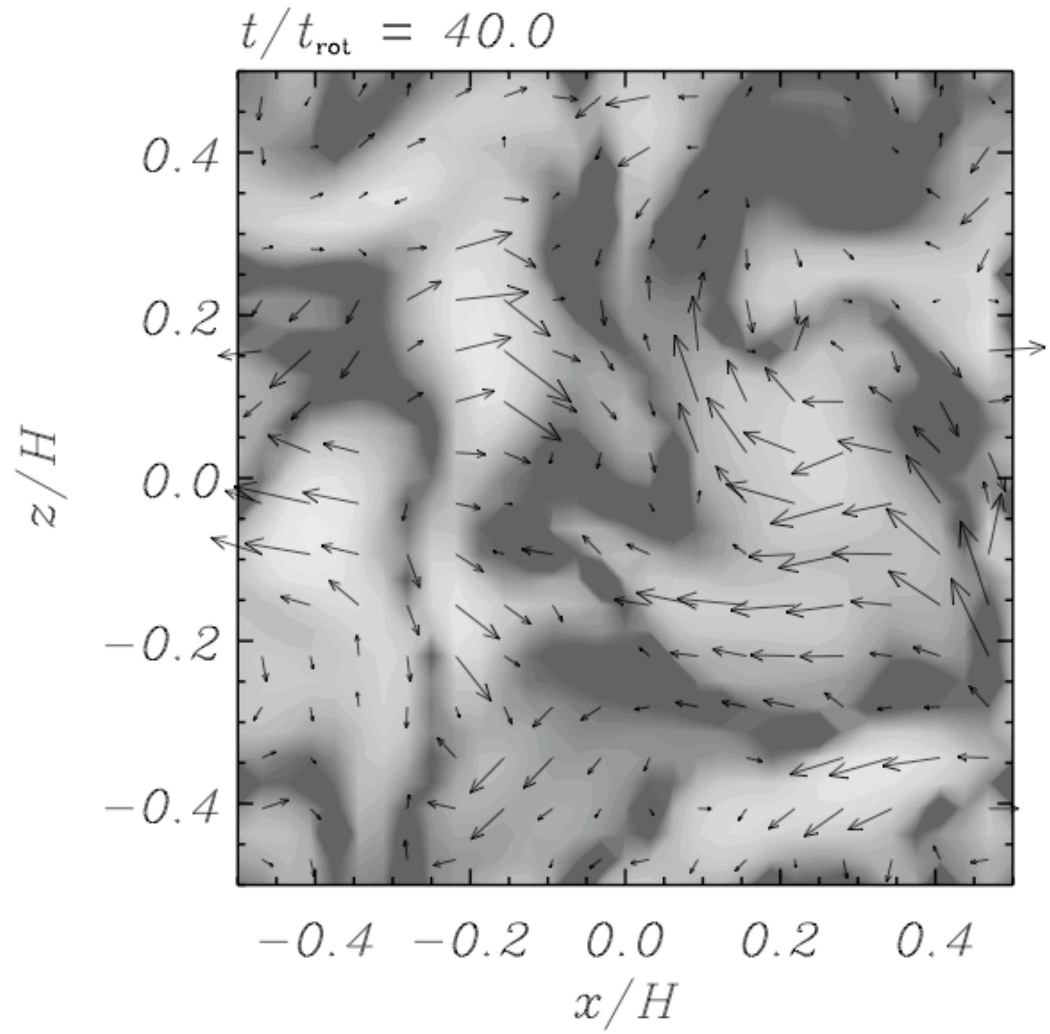
$$v_A = B / (4\pi\, \rho)^{1/2} < C / \sqrt{3}$$

End result is magnetic turbulence. Magnetic fields tangled on small scales.

Net positive time- and spac
averaged Reynolds stress
$R_{r\phi} = \rho <v_r\ v_\phi>$

And Maxwell stress
$M_{r\phi} = <B_r\ B_\phi> / 4\pi$

$\alpha = T_{r\phi} / P$
$= (R_{r\phi} + M_{r\phi}) / P$



Sano & Stone
(2002b) Fig 11

How Strong is the MRI?

Pessah et al. (2007) analyzed 35 different numerical simulations of the MRI in the literature

They find that α is a function of numerical resolution, among other factors.

Extrapolating their formula to the solar nebula, one would predict $\alpha = 0.5$, the theoretical limit **in the absence of magnetic diffusion**.

Observations of fully ionized disks (dwarf novae, etc.) support $\alpha \sim 0.1$ [King et al. 2007]

How Strong is the MRI *in PPDs*?

Observations of viscous spreading (R vs. t) in protoplanetary disks in Taurus suggests $\alpha < 10^{-2}$ [Hartmann et al. 1998], lower than in other disks. PPDs are not fully active everywhere.

Mass accretion rates onto protostars ~ $10^{-8}\ M_\odot\ yr^{-1}$ (Gullbring et al. 1998). Implies relationship between surface density of accreting material and α (Gammie 1996):

$$\dot{M} \sim 10^{-8} \left(\frac{\alpha}{0.01}\right) \left(\frac{\Sigma_\mathrm{a}}{100\,\mathrm{g\,cm^{-2}}}\right) M_\odot\,\mathrm{yr}^{-1}$$

If $\alpha = 0.01$, $\Sigma_a = 100\ g\ cm^{-2}$

If $\alpha = 0.1$, $\Sigma_a = 10\ g\ cm^{-2}$

Either way, $\Sigma_a << \Sigma$ in disk… not all the disk is active.

Limits on the MRI

MRI affected by three types of magnetic diffusion:

Ohmic dissipation: collisions slow down charge carriers, diminishing currents that are essential to magnetic forces; always stabilizes the gas

Ambipolar Diffusion: decoupling between neutral gas and the ionized fluid; important at lower densities; not always stabilizing

Hall diffusion: E x B drift generates circularly polarized waves that can directly transfer angular momentum without large-scale magnetic forces. Under fine-tuned circumstances is completely destabilizing; but usually is stabilizing.

Limits on the MRI

MRI affected by three types of magnetic diffusion:

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \left(\frac{d\Omega}{d \ln r}\right) B_r \hat{\boldsymbol{e}}_\phi =$$
$$- \nabla \times [\mathcal{D}_{\rm OD}(\nabla \times \boldsymbol{B}) + \mathcal{D}_{\rm AD}(\nabla \times \boldsymbol{B})_\perp + \mathcal{D}_{\rm H}(\nabla \times \boldsymbol{B})_\perp \times \hat{\boldsymbol{e}}_B]$$

$$\mathcal{D}_{\rm OD} = \frac{c^2}{4\pi}\left(\frac{1}{\sigma_\parallel}\right),$$
$$\mathcal{D}_{\rm AD} = \frac{c^2}{4\pi}\left(\frac{\sigma_\perp}{\sigma_\perp^2 + \sigma_{\rm H}^2} - \frac{1}{\sigma_\parallel}\right),$$
$$\mathcal{D}_{\rm H} = -\frac{c^2}{4\pi}\left(\frac{\sigma_{\rm H}}{\sigma_\perp^2 + \sigma_{\rm H}^2}\right).$$

$$\sigma_\parallel = \sum_a \sigma_a,$$
$$\sigma_\perp = \sum_a \frac{\sigma_a}{1 + (\omega_a \tau_{an})^2},$$
$$\sigma_{\rm H} = \sum_a \frac{\sigma_a(\omega_a \tau_{an})}{1 + (\omega_a \tau_{an})^2},$$

$$\sigma_a = n_a q_a^2 \tau_{an} / m_a \qquad \omega_a = q_a B / m_a c$$

$$\tau_{an} = \frac{m_a + m_{\rm n}}{m_{\rm n}} \frac{1}{n_{\rm n} < \sigma w >_{an}}$$

Limits on the MRI

Combine magnetic evolution equation with force equation,

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} - 2\Omega v_\phi \hat{\boldsymbol{e}}_r + \frac{\kappa^2}{2\Omega} v_r \hat{\boldsymbol{e}}_\phi = \frac{1}{4\pi\rho}(\nabla\times\boldsymbol{B})\times\boldsymbol{B} - \frac{\nabla P}{\rho}$$

To derive dispersion relation for growth of the MRI:

$$\sigma^4 + (\omega_{\rm OD} + \omega_{\rm AD} + \omega_T)\sigma^3 + \mathcal{C}_2\sigma^2 + (\omega_{\rm OD} + \omega_{\rm AD} + \omega_T)\left(\kappa^2\cos^2\theta + \omega_{\rm A}^2\cos^2\iota\right)\sigma + \mathcal{C}_0 = 0,$$

Includes all three types of magnetic diffusion, and

$\mathbf{k} = \mathrm{k_r}\,\mathbf{e}_\mathrm{r} + \mathrm{k_z}\,\mathbf{e}_\mathrm{z}$, and

$\mathbf{B} = \mathrm{B_r}\,\mathbf{e}_\mathrm{r} + \mathrm{B_\phi}\,\mathbf{e}_\phi + \mathrm{B_z}\,\mathbf{e}_\mathrm{z}$

$$g = (\hat{\mathbf{e}}_k \times \hat{\mathbf{e}}_{\rm B}\cdot\hat{\mathbf{e}}_\phi)(\hat{\mathbf{e}}_{\rm B}\cdot\hat{\mathbf{e}}_\phi)(\hat{\mathbf{e}}_k\cdot\hat{\mathbf{e}}_z)$$

Max growth rate = $|\,d\Omega/dr\,|\,/\,2$

$$\mathcal{C}_2 = \kappa^2\cos^2\theta + 2\omega_{\rm A}^2\cos^2\iota + (\omega_{\rm H}\cos\iota)\left[\cos\theta\frac{d\Omega}{d\ln r} + (\omega_{\rm H}\cos\iota)\right] + (\omega_{\rm OD}+\omega_{\rm AD})\omega_T + \omega_{\rm AD}\left(\frac{d\Omega}{d\ln r}\right)g, \qquad (36)$$

$$\mathcal{C}_0 = \left[\omega_{\rm A}^2\cos^2\iota + 2(\Omega\cos\theta)(\omega_{\rm H}\cos\iota) + \frac{d\Omega^2}{d\ln r}\cos^2\theta\right] \times \left[\omega_{\rm A}^2\cos^2\iota + \frac{\kappa^2\cos\theta}{2\Omega}(\omega_{\rm H}\cos\iota)\right] + \kappa^2\cos^2\theta \times (\omega_{\rm OD}+\omega_{\rm AD})\omega_T + \omega_{\rm AD}\left(\frac{d\Omega}{d\ln r}\right) \times \left(\kappa^2\cos^2\theta + \omega_{\rm A}^2\cos^2\iota\right)g,$$

Limits on the MRI

Three possible ways to make $C_0 < 0$ and destabilize the disk:

1. Shear term 2. AD terms 3. Hall terms

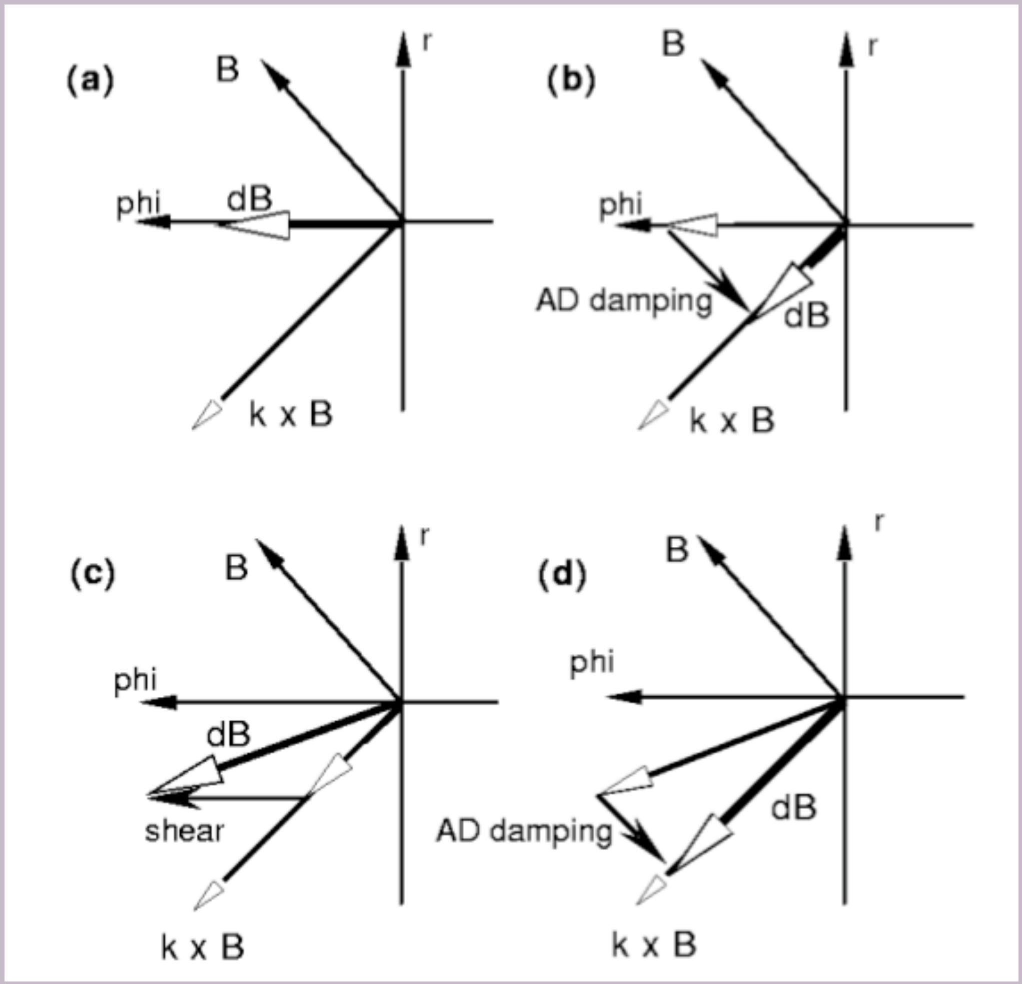
$$\mathcal{C}_0 = \left[\omega_{\rm A}^2 \cos^2\iota + 2(\Omega\cos\theta)(\omega_{\rm H}\cos\iota) + \frac{d\Omega^2}{d\ln r}\cos^2\theta\right]$$
$$\times\left[\omega_{\rm A}^2\cos^2\iota + \frac{\kappa^2\cos\theta}{2\Omega}(\omega_{\rm H}\cos\iota)\right] + \kappa^2\cos^2\theta$$
$$\times(\omega_{\rm OD} + \omega_{\rm AD})\omega_T + \omega_{\rm AD}\left(\frac{d\Omega}{d\ln r}\right)$$
$$\times\left(\kappa^2\cos^2\theta + \omega_{\rm A}^2\cos^2\iota\right)g,$$

$$g = (\hat{\mathbf{e}}_k \times \hat{\mathbf{e}}_{\rm B}\cdot\hat{\mathbf{e}}_\phi)(\hat{\mathbf{e}}_{\rm B}\cdot\hat{\mathbf{e}}_\phi)(\hat{\mathbf{e}}_k\cdot\hat{\mathbf{e}}_z)$$

Desch (2004)

Limits on the MRI

Although ambipolar diffusion is dissipative, it can be destabilizing… for unusual magnetic field geometries



$$g = (\hat{\mathbf{e}}_k \times \hat{\mathbf{e}}_{\mathrm{B}} \cdot \hat{\mathbf{e}}_\phi)(\hat{\mathbf{e}}_{\mathrm{B}} \cdot \hat{\mathbf{e}}_\phi)(\hat{\mathbf{e}}_k \cdot \hat{\mathbf{e}}_z)$$

Desch (2004)

Limits on the MRI

But let's assume $B_r = 0$, $B_\phi = 0$. Then g = 0, AD is stabilizing, and positive growth of linear instability requires

$$\frac{1}{\cos^2\theta}\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}+\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}\right)+\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}+\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)$$
$$\times\left(\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)+\left(\frac{5}{4}+\frac{s\mathcal{D}_{\rm H}}{v_{\rm A}^2/\Omega}\right)^2-\frac{9}{16}<\frac{3\Omega^2}{k^2v_{\rm A}^2}\left(1+\frac{1}{2}\frac{s\mathcal{D}_{\rm H}}{v_{\rm A}^2/\Omega}\right)$$

q = angle between **k** and **B**

Desch (2004)

s = +1 (-1) if **B** parallel (anti-parallel) to disk rotation axis

In general, must consider four geometrical combinations when testing for instability: s = ±1, cosθ = 1 and ~ 0.1

Limits on the MRI

One robust result: Ohmic dissipation is always stabilizing

MRI shuts off if $D_{OD} > C^2 / \Omega$ ($t_{diff} = H^2 / D_{OD} < 1 / \Omega$)

$$\frac{1}{\cos^2\theta}\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}+\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}\right)+\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}+\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)$$
$$\times\left(\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)+\left(\frac{5}{4}+\frac{s\mathcal{D}_{\rm H}}{v_{\rm A}^2/\Omega}\right)^2-\frac{9}{16}<\frac{3\Omega^2}{k^2v_{\rm A}^2}\left(1+\frac{1}{2}\frac{s\mathcal{D}_{\rm H}}{v_{\rm A}^2/\Omega}\right)$$

If $n_e / n_{H2} <$ this critical value, Ohmic diffusion dominates and shuts off MRI

$$\left(\frac{n_{\rm e}}{n_{\rm H2}}\right)_{\rm crit}=8\times10^{-14}\left(\frac{T}{100\,{\rm K}}\right)^{-1/2}\left(\frac{r}{1\,{\rm AU}}\right)^{-3/2}$$

Limits on the MRI

Hall terms can be destabilizing or stabilizing.

$$\frac{1}{\cos^2\theta}\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}+\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}\right)+\left(\frac{\mathcal{D}_{\rm OD}}{v_{\rm A}^2/\Omega}+\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)$$
$$\times\left(\frac{\mathcal{D}_{\rm AD}}{v_{\rm A}^2/\Omega}\right)+\left(\frac{5}{4}+\frac{s\mathcal{D}_{\rm H}}{v_{\rm A}^2/\Omega}\right)^2-\frac{9}{16}<\frac{3\Omega^2}{k^2v_{\rm A}^2}\left(1+\frac{1}{2}\frac{s\mathcal{D}_{\rm H}}{v_{\rm A}^2/\Omega}\right) \quad \text{(UNST)}$$

There is always a limited range of $s\,D_{\rm H}\,/\,(v_{\rm A}^2\,/\,\Omega)$ that will render very short-wavelength modes (k >> 1) unstable. Related to transport of angular momentum by circularly polarized waves [Wardle & Ng 1999]

Range is very small, potentially as small as -2 to -1/2; hard to fine-tune the disk? Also unclear whether a given disk would have the right sign of *s*!

Large $s\,D_{\rm H}\,/\,(v_{\rm A}^2\,/\,\Omega)$ is stabilizing

The MRI in PPDs

Where the MRI occurs in disks depends on abundances of charged particles, which depend on ionization rates and recombination rates, as well as magnetic field.

Possible sources of ionization:

•Galactic cosmic rays, $\zeta \sim 10^{-17}$ s^{-1} [Caselli et al. 1998]; attenuated exponentially by ~ 100 g cm^{-2} of gas [Umebayashi 1981]

•X rays from the central star, $\zeta \sim 3 \times 10^{-11}$ $(r / 1 \text{ AU})^{-2}$ s^{-1} attenuated with depth into the disk by ~ 1 - 10 g cm^{-2} of gas [Glassgold et al. 1997; Igea & Glassgold 1999]

•Radioactivities, e.g., ^{26}Al, $\zeta < 10^{-19}$ s^{-1} [Consolmagno & Jokipii 1978]

•Thermal ionization of K? No; effectively $\zeta << 10^{-20}$ s^{-1} [Desch 1998]

•Solar energetic particles??

The MRI in PPDs

Only cosmic rays and protostellar X rays are worth considering.

As it happens, GCRs are very ineffective; only X rays matter

$$\zeta n_{\mathrm{H2}} = n_{\mathrm{e}}\, n_{\mathrm{gr}}\, \pi a_{\mathrm{gr}}^2\, S_{\mathrm{e}} C_{\mathrm{e}}$$

Recombinations on grain surfaces dominate
when $n_i / n_{H2} < 10^{-8}$ [Desch 2004]

$$\frac{n_{\mathrm{e}}}{n_{\mathrm{H2}}} = 9\times10^{-16} \left(\frac{\zeta}{10^{-16}\,\mathrm{s}^{-1}}\right) \left(\frac{a_{\mathrm{gr}}}{1\,\mu\mathrm{m}}\right) \left(\frac{\rho_{\mathrm{g}}}{10^{-9}\,\mathrm{g\,cm}^{-3}}\right)^{-1} \left(\frac{T}{100\,\mathrm{K}}\right)^{-1/2}$$

Compare to critical value ~ 10^{-13} at 1 AU

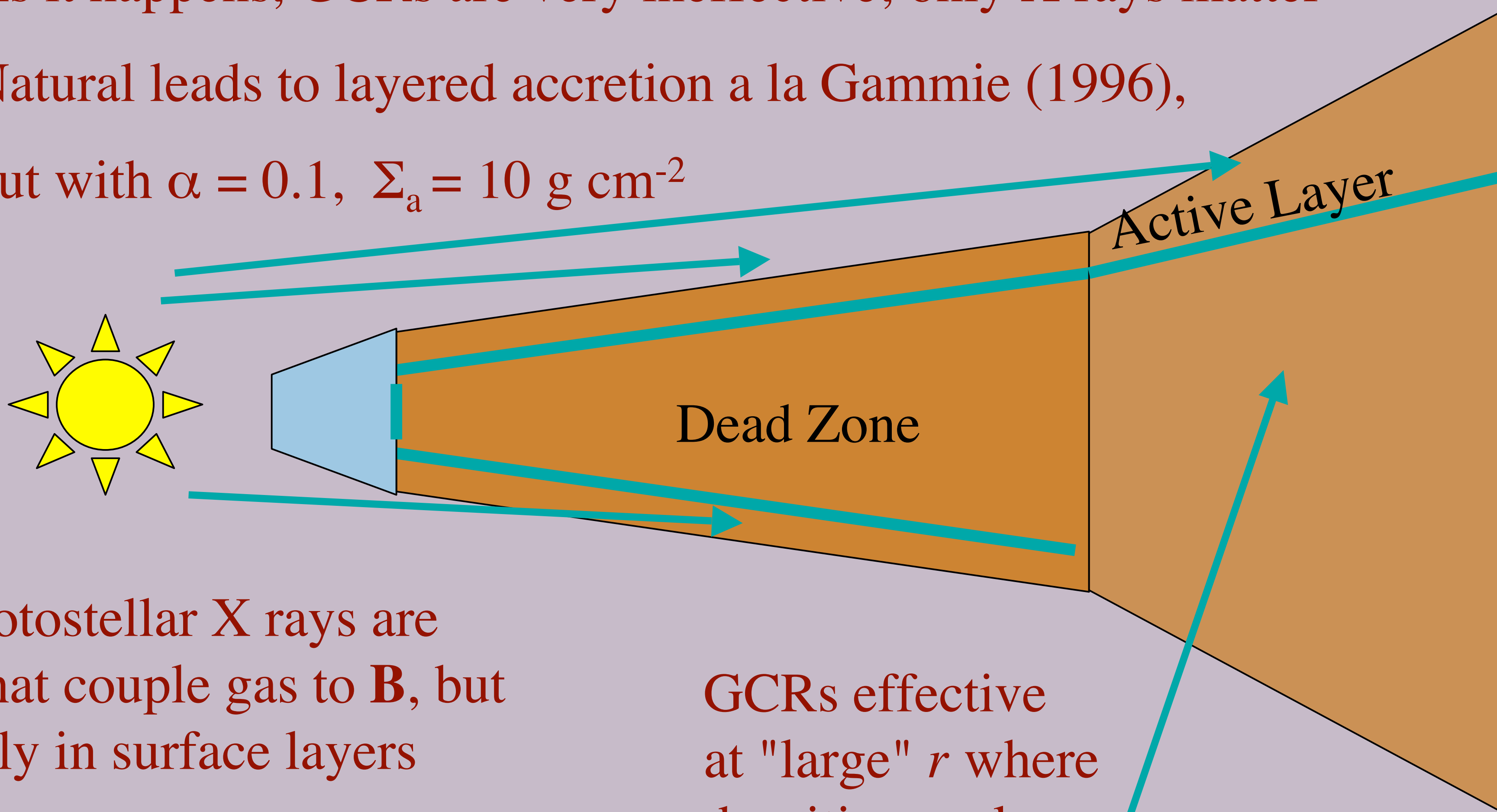
The MRI in PPDs

Only cosmic rays and protostellar X rays are worth considering.

As it happens, GCRs are very ineffective; only X rays matter

Natural leads to layered accretion a la Gammie (1996),

but with $\alpha = 0.1$, $\Sigma_a = 10$ g cm^{-2}



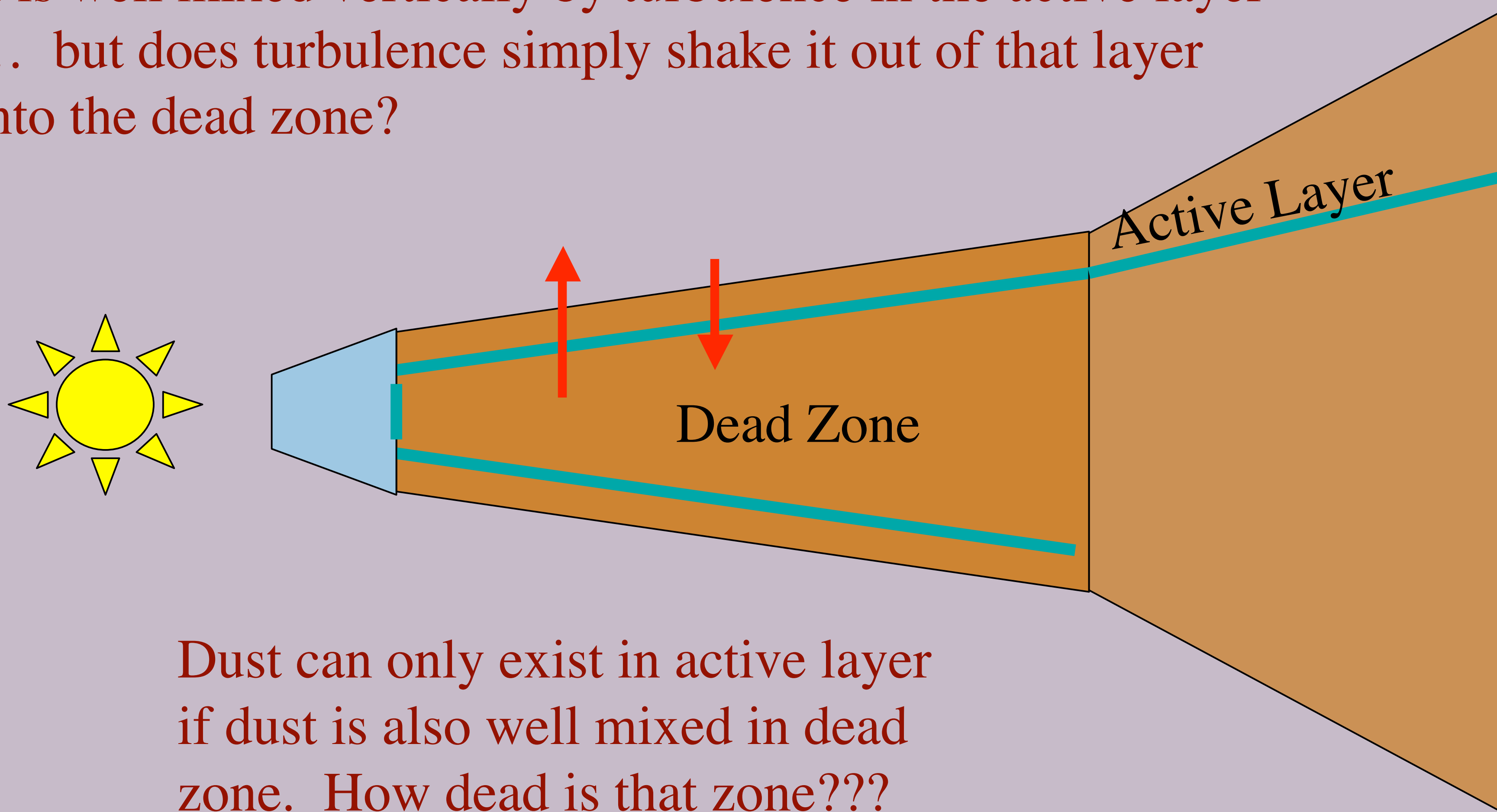
Protostellar X rays are what couple gas to **B**, but only in surface layers

GCRs effective at "large" *r* where densities are low

The MRI in PPDs

Back to the dust…

It is well mixed vertically by turbulence in the active layer … but does turbulence simply shake it out of that layer into the dead zone?



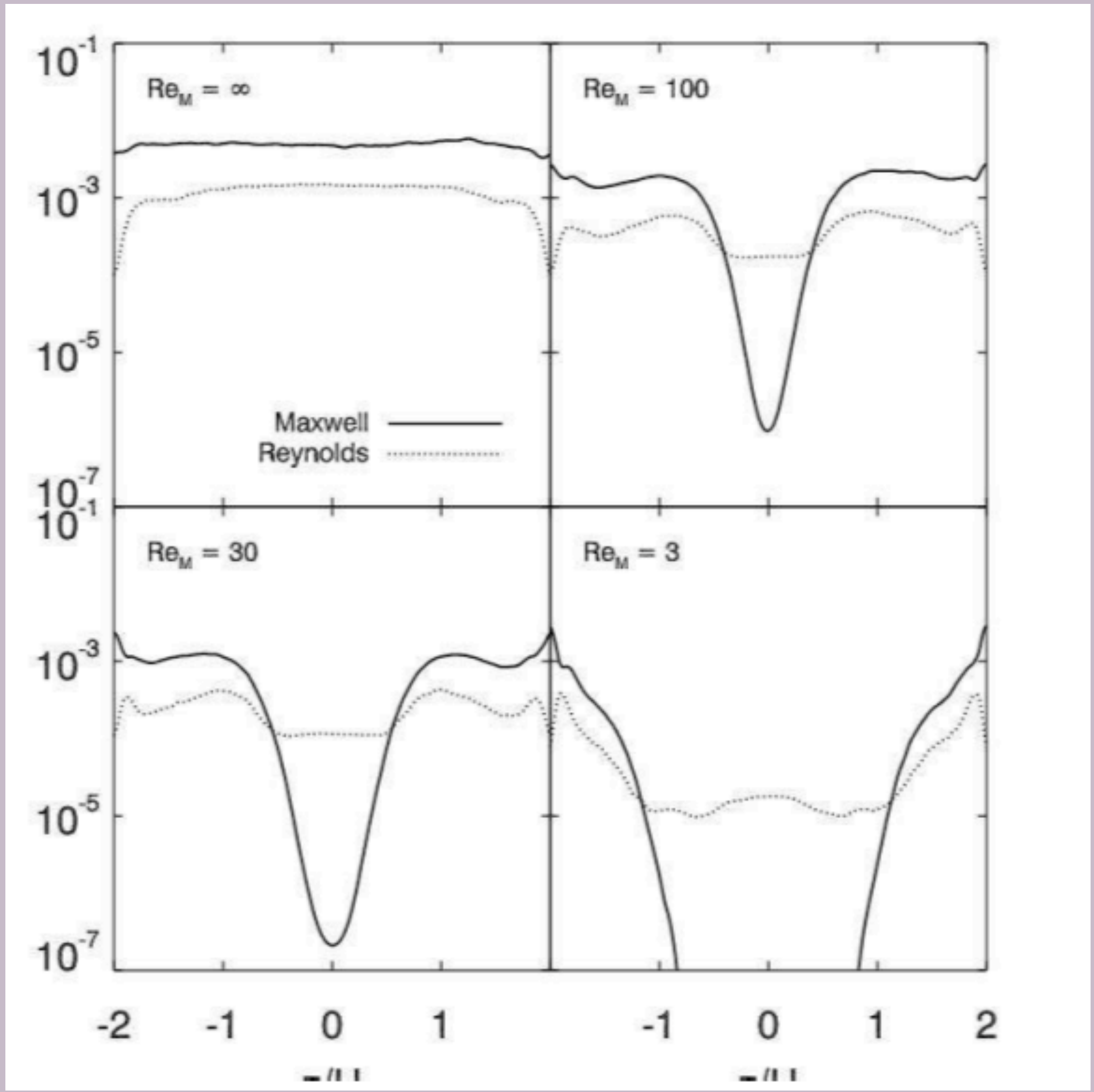
Dust can only exist in active layer if dust is also well mixed in dead zone. How dead is that zone???

The MRI in PPDs

The dead zone is not actually dead; it experiences reduced Reynolds stresses [Fleming & Stone 2003; Oishi et al. 2007]

a in dead zone $\sim 10^{-5}$ to 10^{-4}

Turbulent velocities $\sim \alpha^{1/2}\, C \sim 10^{3}$ cm s^{-1}



Oishi et al. (2007), Fig 2

The MRI in PPDs

$$V_{\rm turb} \sim \alpha^{1/2} c_{\rm s} \sim 10^3 \left(\frac{\alpha}{10^{-4}}\right)^{1/2} \,{\rm cm\,s^{-1}}$$

Random velocities far exceed settling velocities; likely that dust is well mixed throughout disk

$$V_{\rm settle} \approx \frac{\Omega^2 z\,(4\pi/3)\rho_{\rm s} a^3}{\pi a^2\,\rho_{\rm g} c_{\rm s}} \approx \frac{\rho_{\rm s} a}{\Sigma(>z)}\, c_{\rm s}$$

$$V_{\rm settle} \approx 0.3 \left(\frac{a_{\rm gr}}{0.1\,\mu{\rm m}}\right) \left(\frac{\Sigma(>z)}{10\,{\rm g\,cm^{-2}}}\right)^{-1} {\rm cm\,s^{-1}}$$

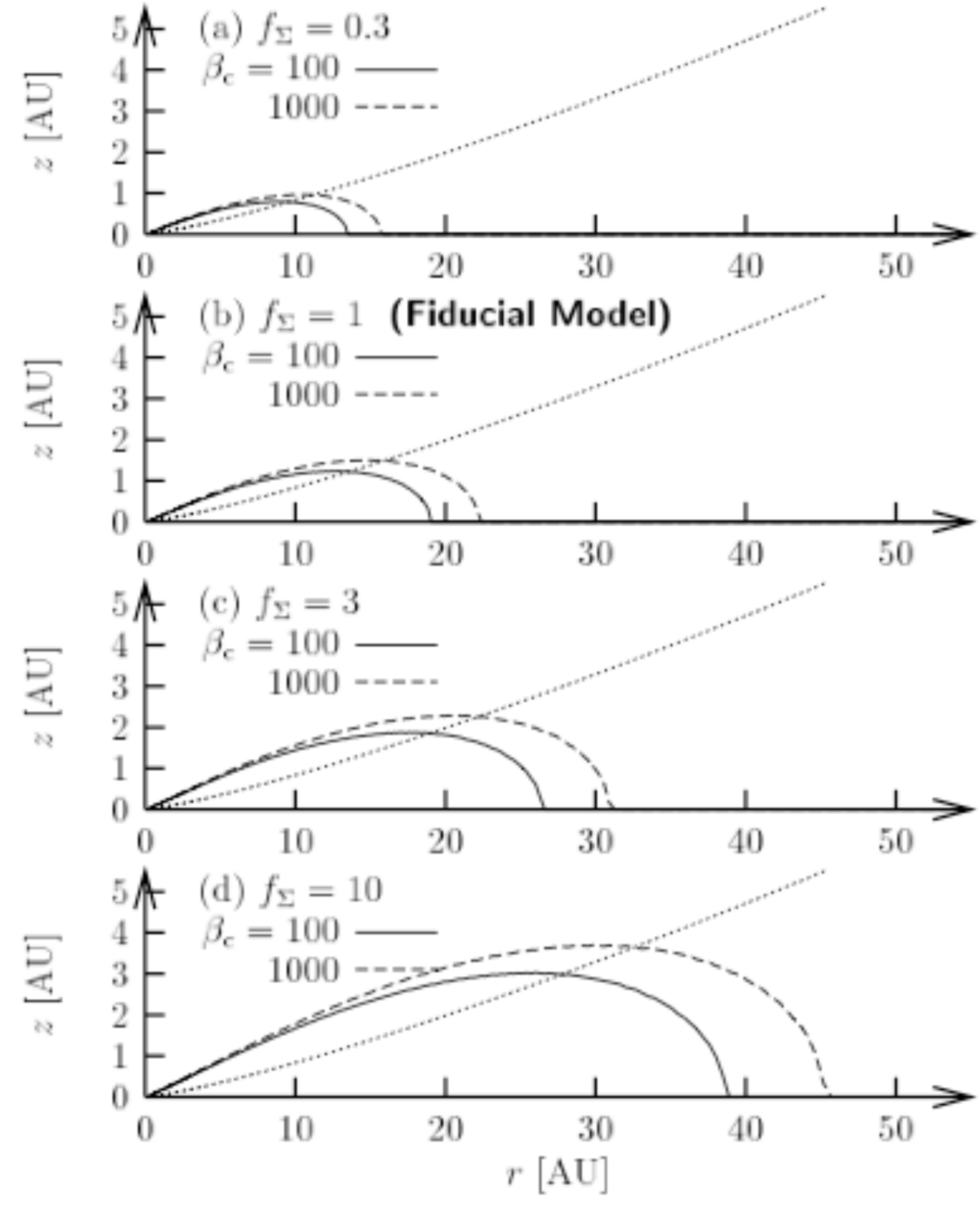
Coagulation per se does not change aerodynamic properties; compaction also neededs

The MRI in PPDs

Calculations of Sano et al. (2000) include detailed chemistry, but considered Ohmic dissipation only, and ionization only by GCRs.

In the standard MMSN, dead zones extend to about 20 AU.

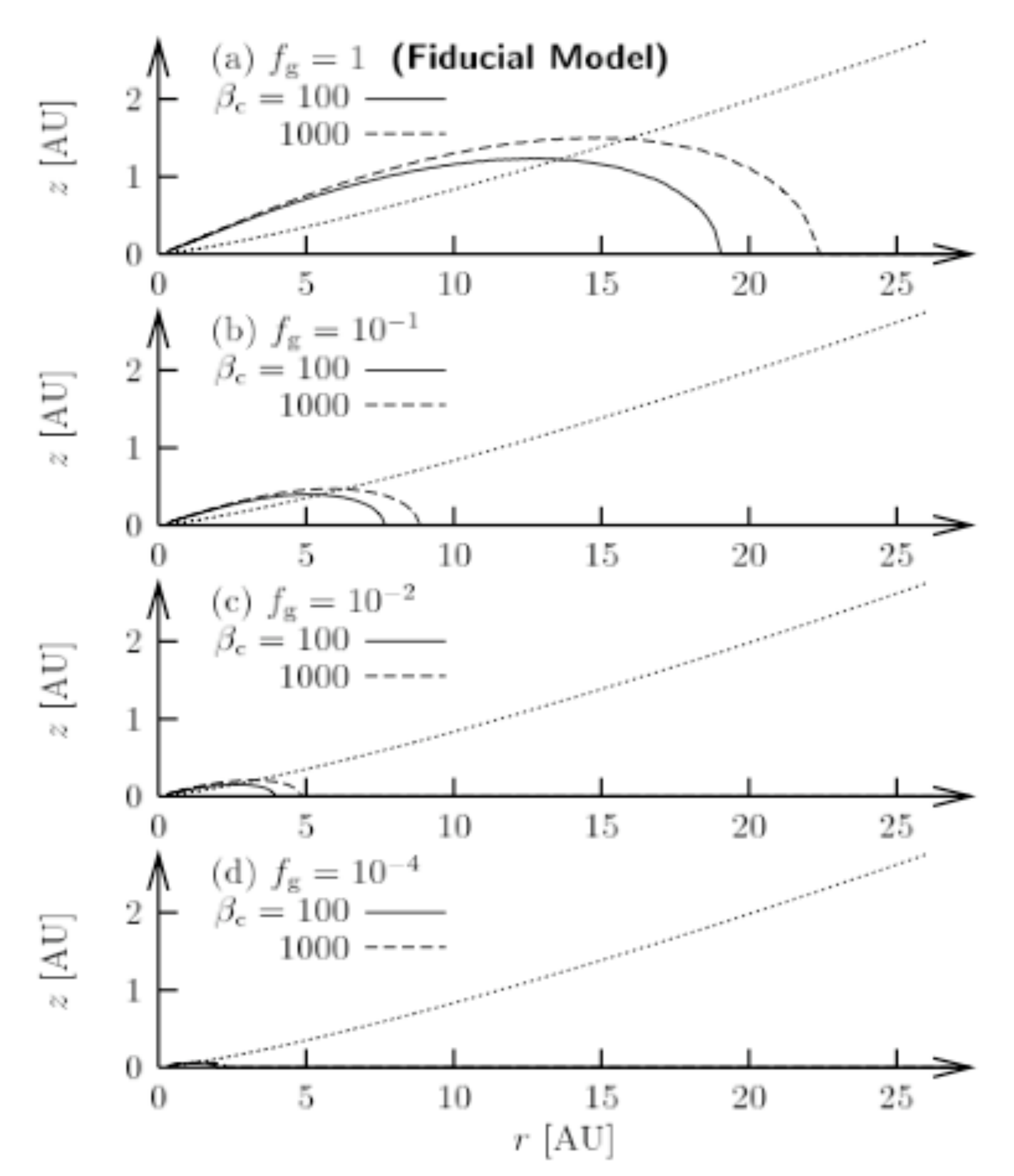
In a denser disk (like Desch 2007) they would extend past 30 AU.



Sano et al. (2000) Fig 8

The MRI in PPDs

Depletion of dust grains a very significant factor.



Sano et al. (2000), Fig 11

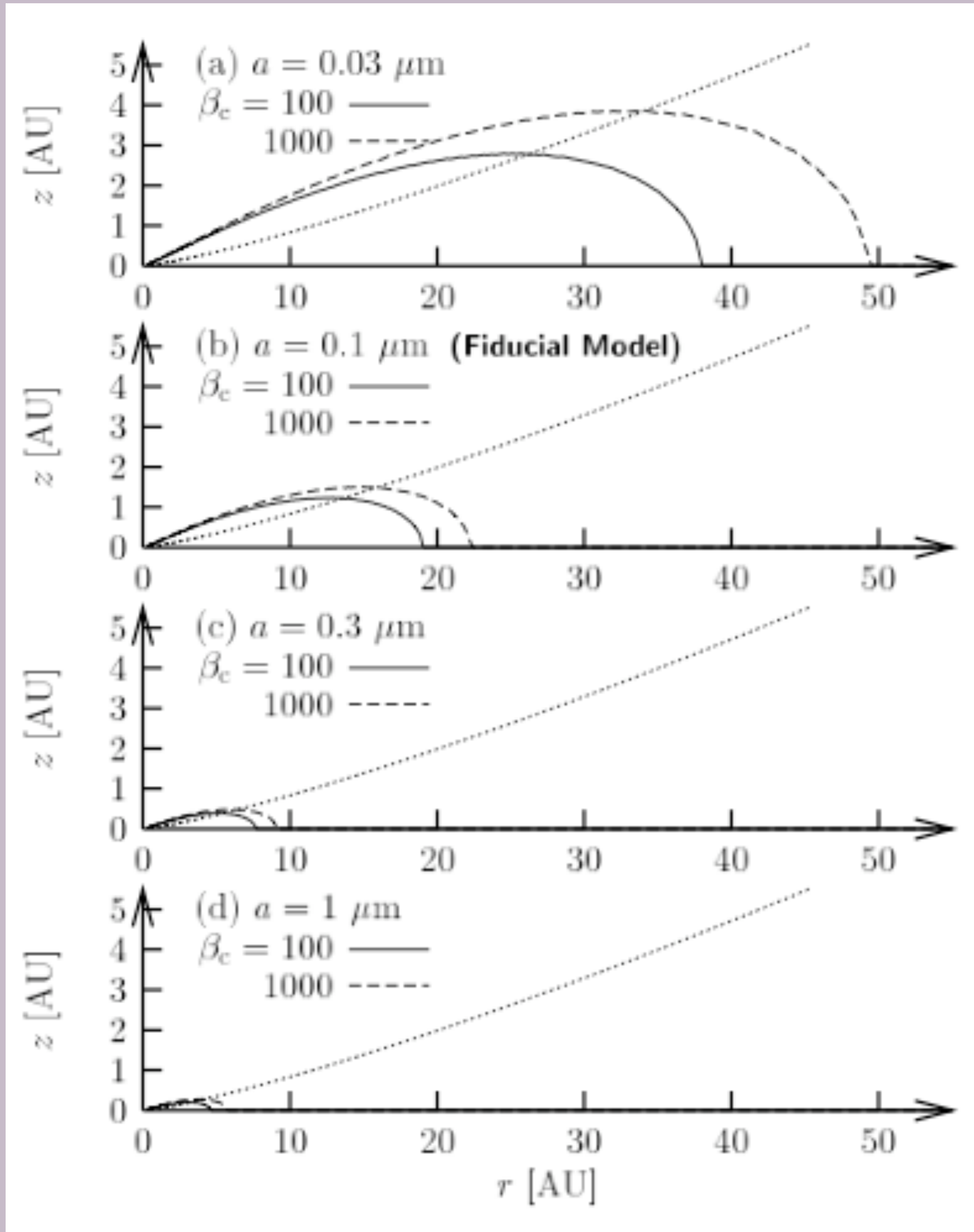
The MRI in PPDs

Size of dust grains a very significant factor.

These calculations ignore Hall effects.

In context of the models, $| s D_H / (v_A^2 / \Omega) | >> 1$ even out past 30 AU.

Hall terms are potentially destabilizing or stabilizing



Sano et al. (2000), Fig 12

Some Speculative Conclusions

Micron-sized dust was present in our disk, and in other disks for several Myr.

Was *probably* well mixed

Recombinations on dust surfaces the dominant mechanism, keeping ionization fraction low

Cosmic rays can ionize gas and raise n_e / $n_{H2} > 10^{-13}$ only beyond a critical radius = 10-30 AU?

Only protostellar X rays can ionize gas in inner disk to couple to field

Active layer ~ 10 g cm^{-2} thick, with high $\alpha \sim 0.1$, leading to mass accretion rates ~ 10^{-8} $M_{\odot}$ yr^{-1}

Some Speculative Conclusions

Dead zones easily could extend to > 30 AU: disk was probably very massive., and Hall effects potentially could be very stabilizing

Effective alpha could be ~ 10^{-4} - 10^{-2} even though MRI is (locally) much more effective.

Future work must include:

- Much more comprehensive chemistry
- Stability based on local magnetic diffusion (OD + AD + Hall)
- Feedbacks between MHD turbulence and B used in diffusivity
- Feedbacks between MRI and thermal structure of disk
- Feedbacks between turbulence and spatial distribution (and size distribution) of dust.

Planetary Migration

The 'Nice' Model (Tsiganis et al. 2005; Gomes et al. 2005; Morbidelli et al. 2005; Levison et al. 2007, 2008) explains:

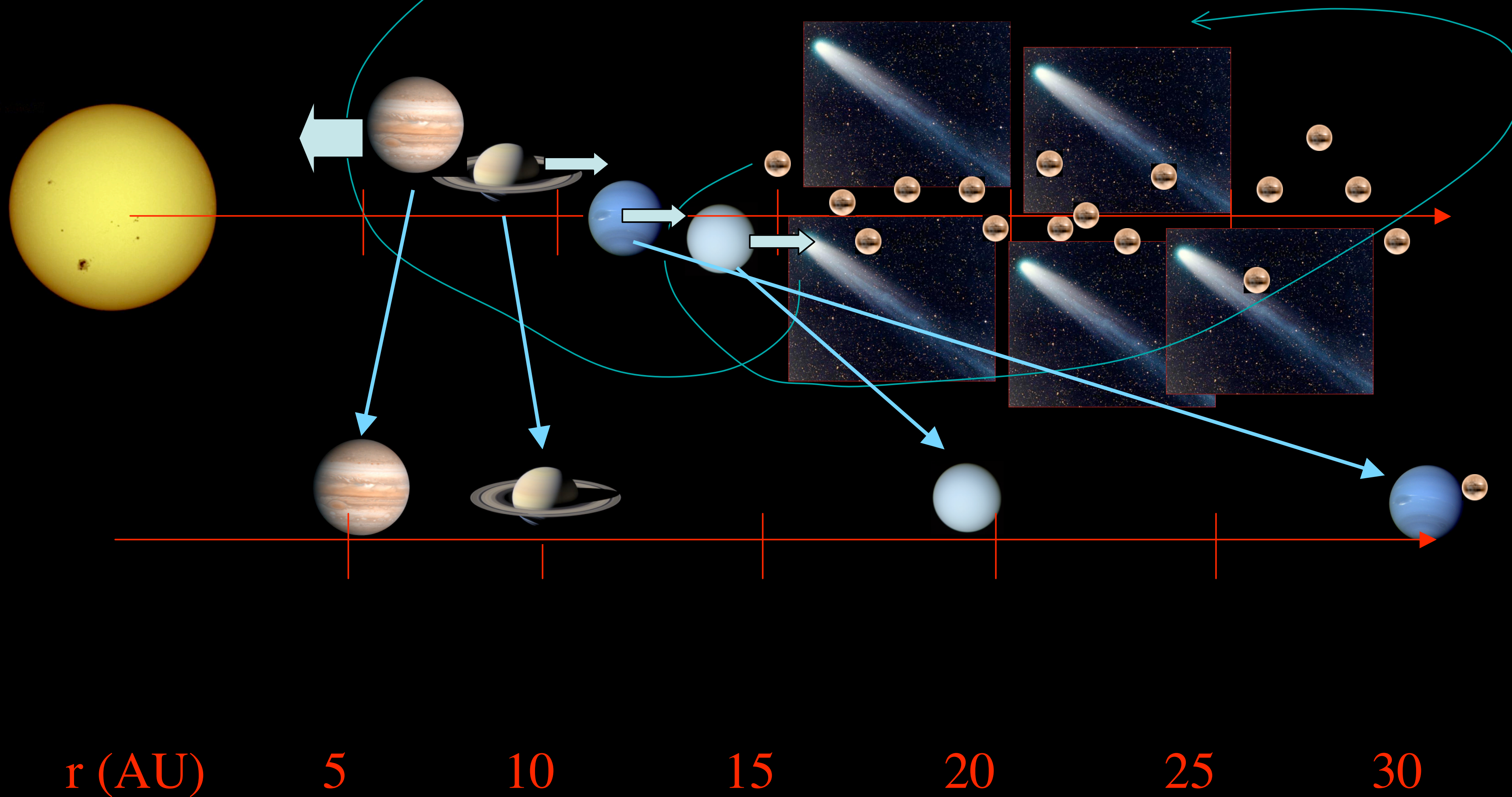
- The timing and magnitude of Late Heavy Bombardment
- Giant planets' semi-major axes, eccentricities and inclinations
- Numbers of Trojan asteroids and irregular satellites
- Structure of Kuiper Belt, etc.

IF

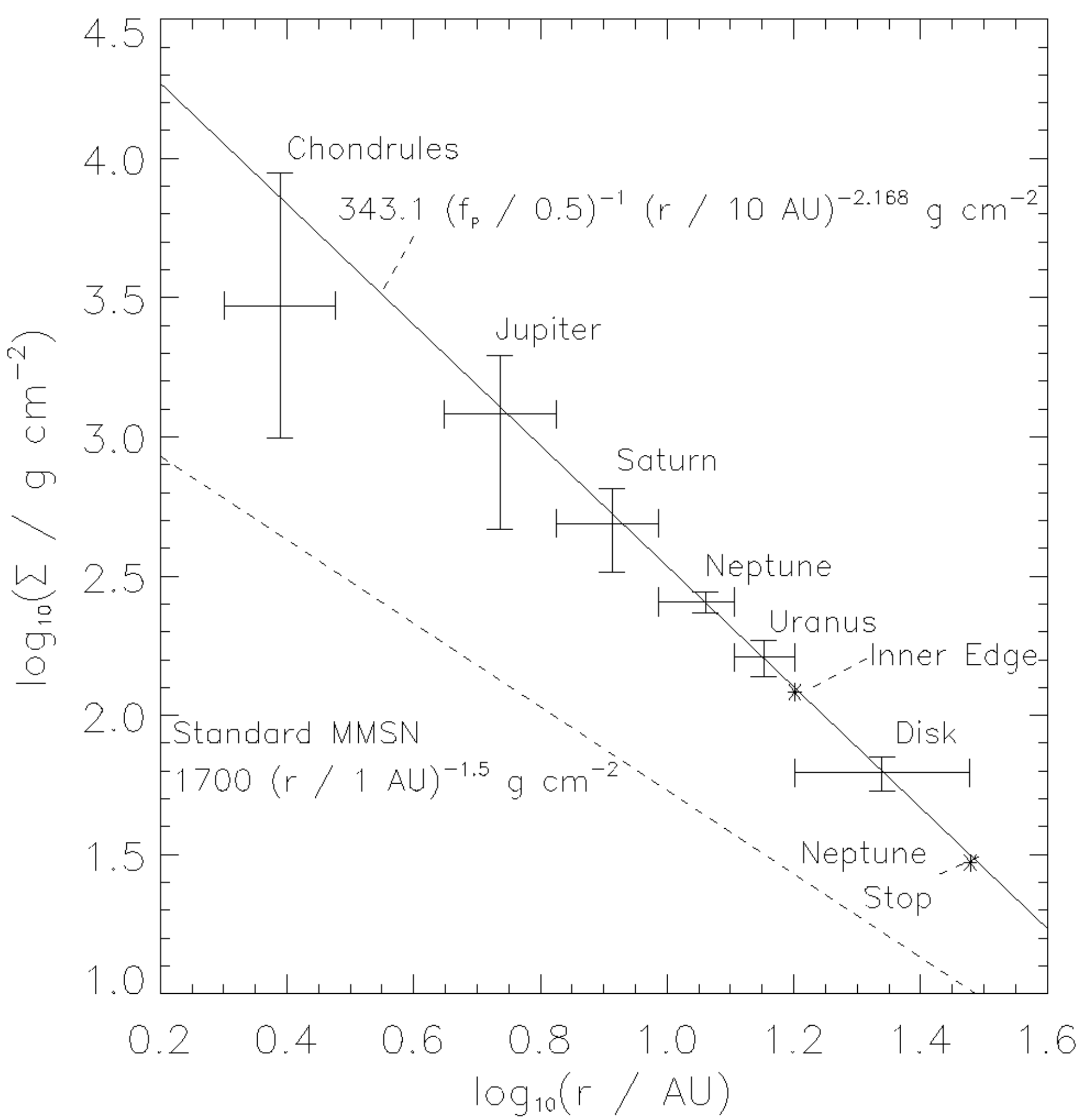
- Planets formed at 5.45 AU (Jupiter), 8.18 AU (Saturn), 11.5 AU (Neptune / Uranus) and 14.2 AU (Uranus / Neptune)
- A 35 $M_{\oplus}$ Disk of Planetesimals extended from 15 - 30 AU
- Best fits involve encounter between Uranus and Neptune; in 50% of simulations they switch places

Planetary Migration

2:1 resonance crossing occurs about 650 Myr after solar system formation



New Minimum Mass Solar Nebula



Disk much denser!

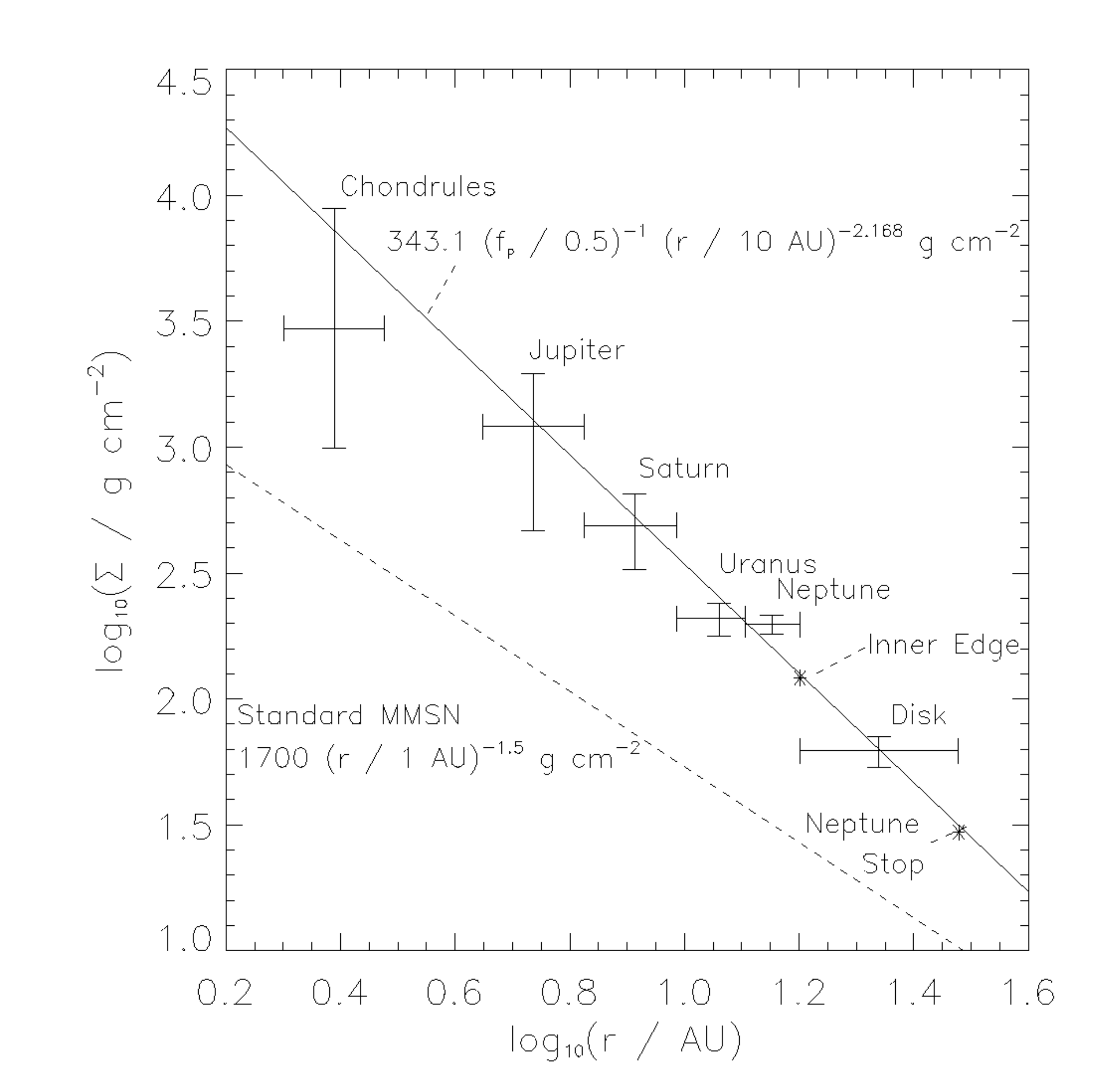
Disk much more massive: 0.092 $M_\odot$ from 1-30 AU; vs. 0.011 $M_\odot$

Density falls steeply (as $r^{-2.2}$) but very smoothly and monotonically! Matches to < 10%!!

Consistent with many new constraints

Desch (2007)

New Minimum Mass Solar Nebula



Mass distribution is not smooth and monotonic if Uranus and Neptune did not switch orbits.

Very strong circumstantial evidence that Neptune formed closer to the Sun

Desch (2007)

New Minimum Mass Solar Nebula

Steep profile $\Sigma(r) = 343\ (r\ /\ 10\ AU)^{-2.17}\ g\ cm^{-2}$ is *not* consistent with steady-state alpha accretion disk (Lynden-Bell & Pringle 1974)

$$\Sigma(r) = \frac{\dot{M}}{3\pi\nu(r)}\left[1 - \left(\frac{R_\star}{r}\right)^{1/2}\right] \approx \frac{\dot{M}}{3\pi\nu(r)}$$

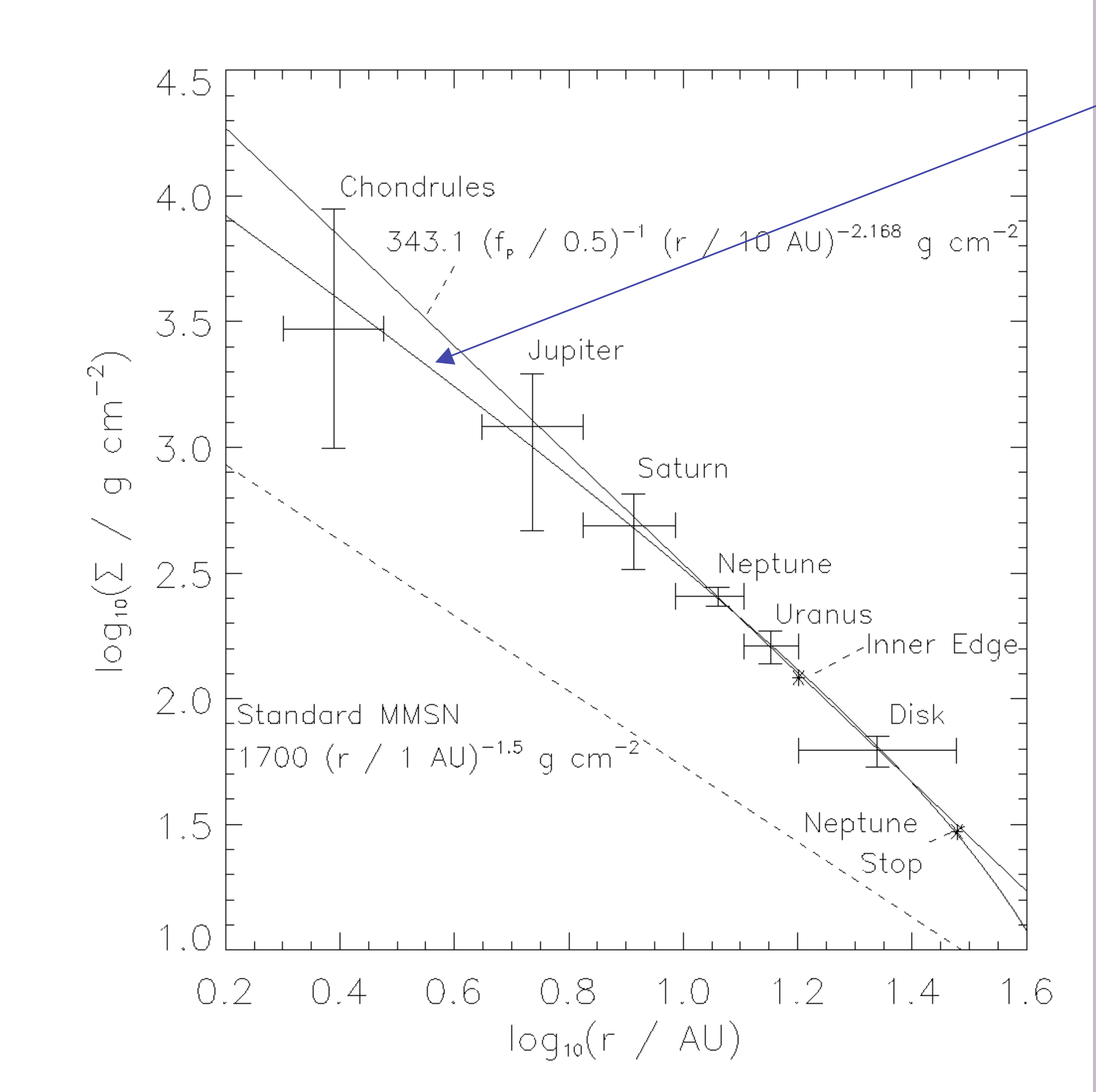
In fact, if $\Sigma \sim r^{-p}$ and $T \sim r^{-q}$ and $p+q > 2$, mass *must* flow outwards (Takeuchi & Lin 2002)

Desch (2007) solved steady-state equations for alpha disk (Lynden-Bell & Pringle 1974) with an *outer* boundary condition due to photoevaporation. Found a steady-state alpha disk solution if solar nebula was a ***de***cretion disk

$$\Sigma(r) = \frac{(-\dot{M})}{3\pi\nu(r)}\left[\left(\frac{r_{\rm d}}{r}\right)^{1/2} - 1\right]$$

Two parameters: α (~ 3 x 10^{-4}), and disk outer edge r_d (~ 50 AU)

New Minimum Mass Solar Nebula



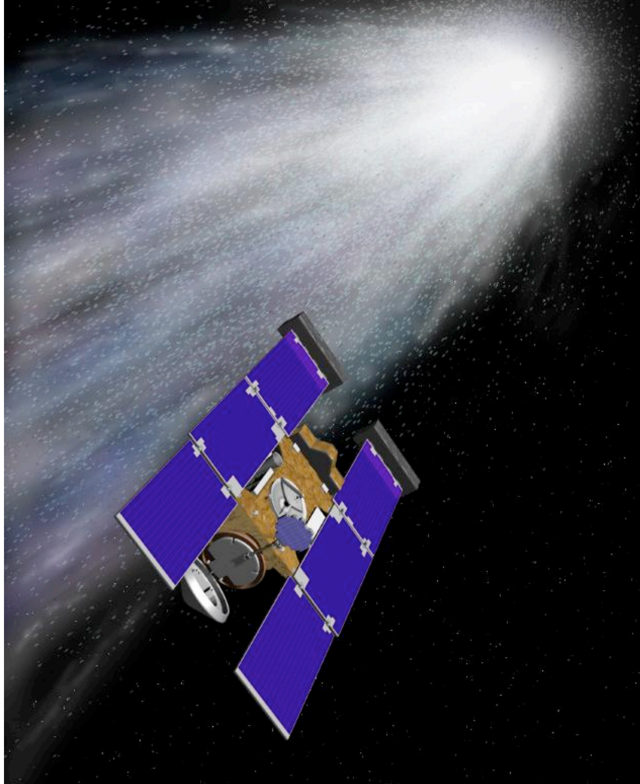
Steady-state alpha decretion disk fits even better.

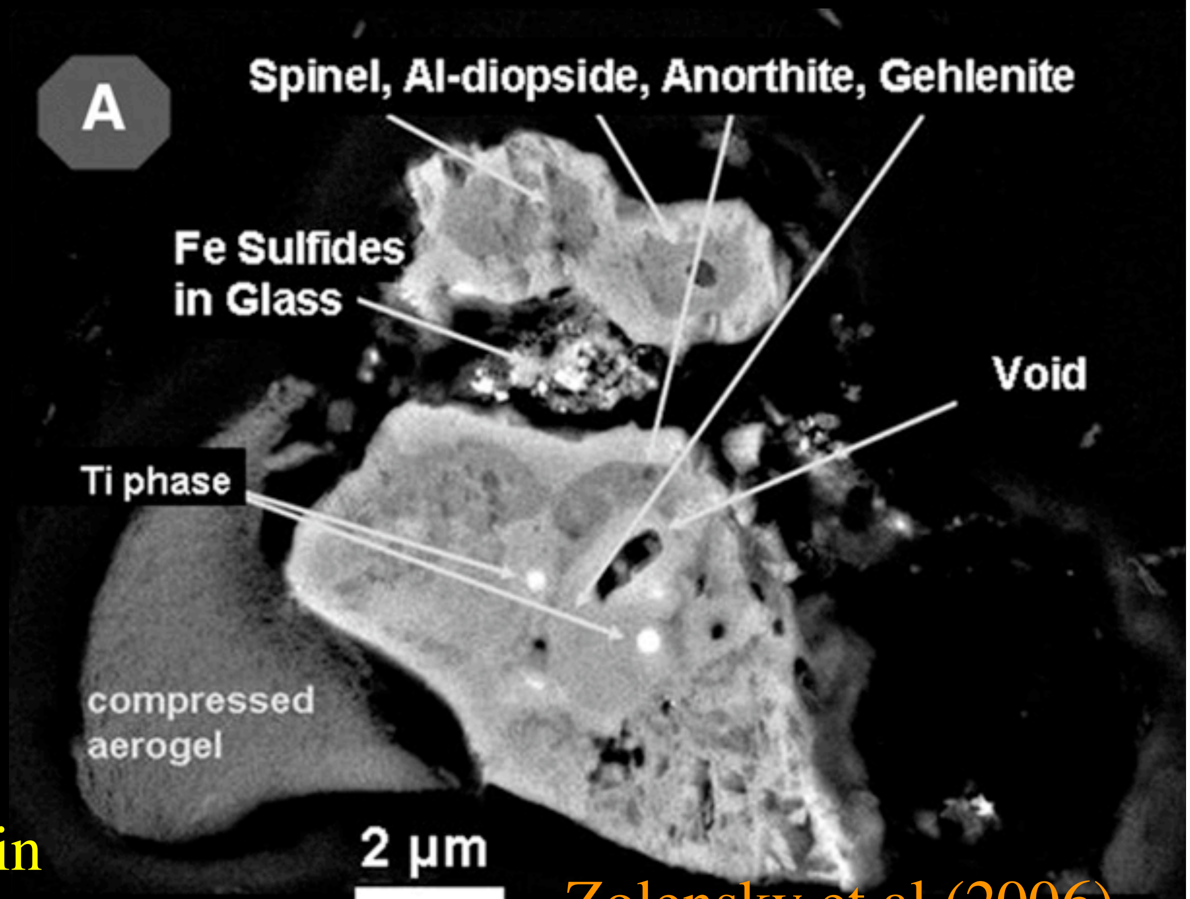
Applies in outer solar system (> few AU)

Applies when large planetesimals formed and dynamically decoupled from gas (a few x 10^5 yrs)

Small particles will trace the gas and move outward in a

Explains presence of CAIs in comets!





Zolensky et al (2006)

Comet 81P/Wild 2

Scattered into present orbit in 1974; was previously a member of the Kuiper Belt Scattered Disk

Probably ***formed*** at 10-30 AU

Stardust Sample Track 25 called 'Inti'. It's a CAI, formed (by condensation) at > 1700 K.

New Model Explains Rapid Growth of Planet Cores

•Planets form closer to Sun in Nice model: orbital timescales faster

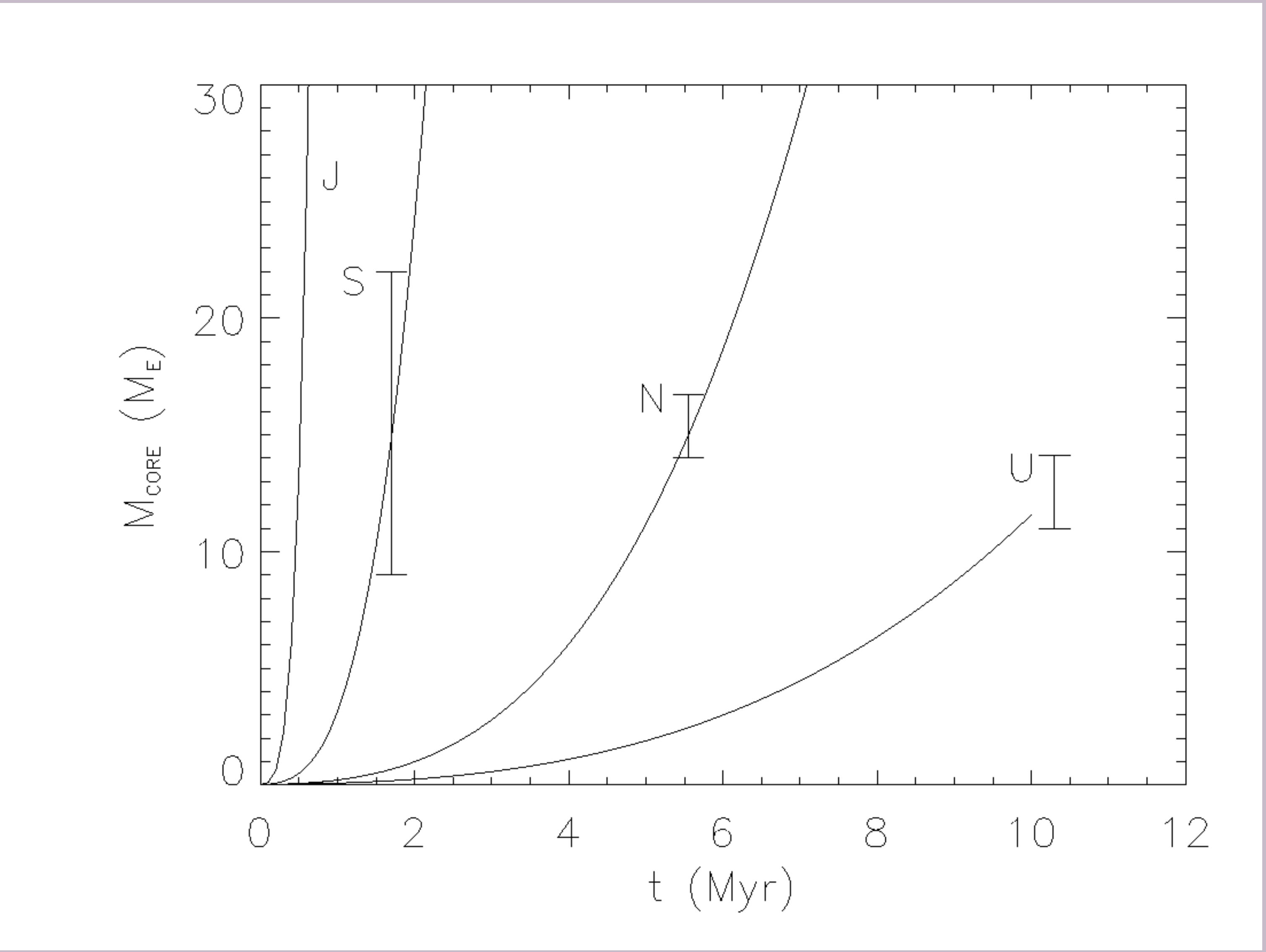
•Density of solids higher than in traditional MMSN

•Higher gas densities damp eccentricities of planetesimals, facilitating accretion

•Desch (2007) calculated growth rate of planetary cores using formulism of Kokubo & Ida (2002).

•Tidal disruption considered; assumed mass of planetesimals $\sim 3 \times 10^{12}$ g (R = 0.1 km, i.e., comets).

- Cores grow in 0.5 Myr (J), 2 Myr (S), 5-6 Myr (N) and 9-11 Myr (U)
- Even Uranus and Neptune reach 10 $M_\oplus$ before H, He gas gone



Summary

Past planet migration implies solar nebula was more massive and concentrated than thought.

Using Nice model positions, Desch (2007) found new MMSN model. Mass ~ 0.1 $M_\odot$, $\Sigma(r) \sim r^{-2.2}$. Strongly implies Uranus and Neptune switched orbits.

Cannot be in steady-state accretion; but $\Sigma(r)$ is consistent with outer solar system as a steady-state alpha ***de***cretion disk being photo-evaporated at about 60 AU (like in Orion)

Dust (read: Inti) would have moved from a few AU to comet-forming zone in a few Myr

All the giant planet cores could reach 10 $M_\oplus$ and accrete H, He gas in lifetime of the nebula